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A Widely Tunable Full Duplex Transceiver Combining Electrical Balance Isolation and Active Analog Cancellation

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***Abstract*—Electrical balance duplexers can provide high transmit-to-receive isolation whilst facilitating transmission and reception from a single antenna, can be implemented on-chip, and are widely tunable, making this an attractive technology for implementing full duplex architectures in small form factor devices. This paper presents measurements from a novel hardware prototype full-duplex transceiver architecture combining electrical balance and active analog cancellation. The prototype duplexer achieves >80dB transmit-to-receive isolation over a 20MHz bandwidth at both 890MHz and 1890MHz, exceeding the performance of antenna separation architectures where the antenna isolation is limited to the levels achievable in hand held devices.**

I. Introduction

Demand for radio services is increasing exponentially, however, the finite nature of the usable radio spectrum means that this rapid growth in consumer demand cannot be met by corresponding increases in the allocated spectrum. Increased demand must therefore be met by increasing spectral efficiency. A long held assumption in wireless communication is that it is not possible to transmit and receive on the same frequency at the same time due to self-interference. However, recent research [1]–[9] has challenged this paradigm, with novel Full-Duplex radio transceivers allowing for simultaneous transmission and reception at the same frequency. Full-duplex systems require just half of the spectral resources as compared to conventional Frequency Division Duplex (FDD) and Time Division Duplex (TDD) systems, theoretically doubling spectral efficiency. Full-Duplex operation requires high transmit-to-receive (TX-RX) isolation, such that self-interference is reduced to an acceptably low level. For a wifi system, over 115dB of TX-RX isolation is typically required in order to reduce the self-interference to a negligible amplitude. To achieve such high isolation, full duplex transceivers invariably combine multiple methods, such as antenna separation, propagation domain cancellation, Radio Frequency (RF) cancellation, and digital baseband cancellation, to suppress the self-interference signal at the receiver [5].

A simple but effective method of providing some transmit to receive isolation is to use separate antennas for transmission and reception. RF cancellation techniques can then be used to further suppress the self-interference picked up by the receiving antenna. The system reported in [2] uses antenna separation along with *active cancellation* [9]–[12], utilizing an additional transmit chain to generate the cancellation signal, as depicted in 1(a). This system demonstrates impressive TX-RX isolation up to 81dB over a 10MHz bandwidth, however, the isolation is fundamentally limited by the physical separation of the antennas [2], [13], [14]. Whilst well suited to basestation applications, this architecture is less attractive for mobile devices, where device size and form factor are important design considerations. The now common requirement for MIMO would further increase the number of antennas, and an antenna separation based full duplex MIMO transceiver could be particularly large. Single antenna full duplex systems combining circulators and analog cancellation have been reported in [4], [15]. The prototype in [4] combines a circulator with *passive cancellation* [1], wherein the analog transmit signal is tapped just prior to the antenna, and is processed in RF circuitry

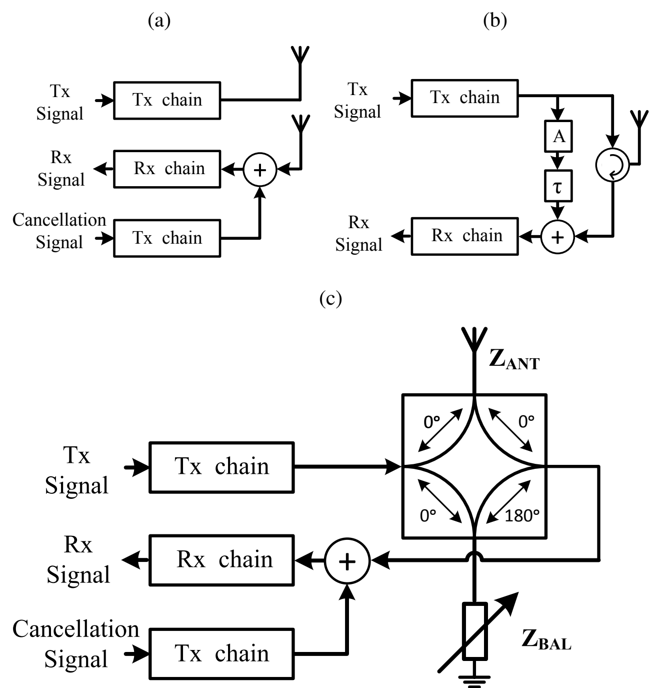

Fig. 1: Full duplex architectures: (a) Antenna separation and active analog cancellation [2]. (b) Circulator and passive analog cancellation [4]. (c) Electrical balance and active analog cancellation.

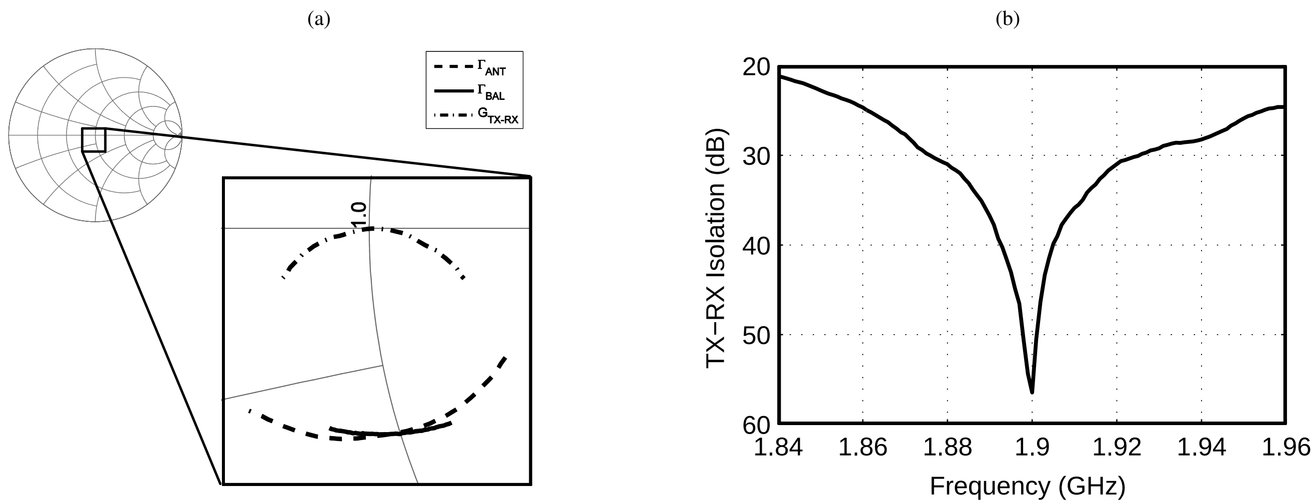

Fig. 2: Impedances and gain measurements from a prototype EB duplexer. (a) Smith chart showing impedance trajectories for the antenna and balancing network, and the resulting TX-RX gain. Trajectories are plotted over a 40MHz band centred at 1.9GHz. (b) Magnitude of the resulting TX-RX isolation ($|G_{TX-RX}|$), plotted over a 120MHz bandwidth.

to produce the cancellation signal, as depicted in Fig. 1(b). Although this system provides substantial isolation of over 70dB, and is better suited to MIMO [15], [16], the use of a circulator is a potential drawback, as these components are typically bulky and expensive, and exhibit limited bandwidth and tunability. Circulator based systems may therefore also be an unattractive option for small form factor full duplex devices, although recent advances in electronic circulator technology may mitigate these drawbacks in the future [17]. Electrical Balance (EB) duplexing is an alternative technique for coupling the TX and RX to a shared antenna whilst providing high TX-RX isolation, and has recently been studied as a potential duplexing architecture for FDD transceivers [18], [19] and full duplex transceivers [8], [20], [21].

In this paper, we present results for a novel full duplex architecture which combines EB duplexing with active analog cancellation. This Electrical Balance and Active Cancellation (EBAC) architecture, first proposed by the authors in [20], provides >80dB of TX-RX isolation over a 20MHz bandwidth, making its performance comparable to the alternative architectures discussed above, but requiring just one antenna. EBAC can also be implemented on-chip, and is inherently tunable over a wide frequency range, making it an attractive architecture for implementing full duplex in small form factor multi-band devices. Section II discusses EB duplexing and its limitations, and examines analog cancellation techniques and their suitability for combination with EB. Section III describes the experimental setup and results, comparing EBAC performance against alternative architectures. Section IV concludes.

II. Self-interference Cancellation Techniques

A. Electrical Balance Duplexing

Recent results [18]–[22] have demonstrated that electrical balance in hybrid junctions can be exploited to provide high transmit to receive isolation whilst allowing the use of a shared antenna for transmission and reception. This is achieved by coupling the transmitter, receiver and antenna using a four port hybrid junction, along with a variable balancing impedance connected to the fourth port, as depicted in 1(c). By controlling the balancing impedance such that it is equal to the antenna impedance, high transmit to receive isolation can be achieved. The antenna impedance can exhibit significant time-domain variation due to device motion and user interaction [23], and therefore the balancing impedance must adaptively track the antenna impedance to maintain isolation. A drawback of the EB duplexer is high insertion loss. For an ideal symmetrical EB duplexer 3dB loss is introduced into both the TX and RX paths, however, using an asymmetrical hybrid junction and a noise matched receiver design can mitigate these losses [18], [19], and the penalty in terms of TX efficiency and RX noise figure can be comparable to that introduced by the splitters, circulator, and coupler used in [4]. Hardware EB duplexers reported in [18], [19] achieved extremely wide isolation bandwidths (a 50dB isolation bandwidth of >250MHz is reported in [18]), however these prototypes did not incorporate real antennas. Simulations including measured antenna data presented in [8], [20], and recent results for a hardware prototype duplexer reported in [21], demonstrate that the variation in antenna impedance with respect to frequency significantly reduces the isolation bandwidth, and is the dominant factor in determining the TX-RX isolation of the duplexer. It can be shown [18], that the TX-RX power gain of an ideal EB duplexer is given by

$$G_{Tx-Rx}(\omega) = \frac{1}{4}\left|\Gamma_{BAL}(\omega) - \Gamma_{ANT}(\omega)\right|^2 \quad (1)$$

where Γ_{BAL} and Γ_{ANT} are the complex reflection coefficients of the balancing impedance and antenna impedance respectively. Clearly, setting the balancing reflection coefficient to equal the antenna reflection coefficient at the carrier frequency, ω_c, such that $\Gamma_{BAL}(\omega_c) = \Gamma_{ANT}(\omega_c)$, will result in extremely

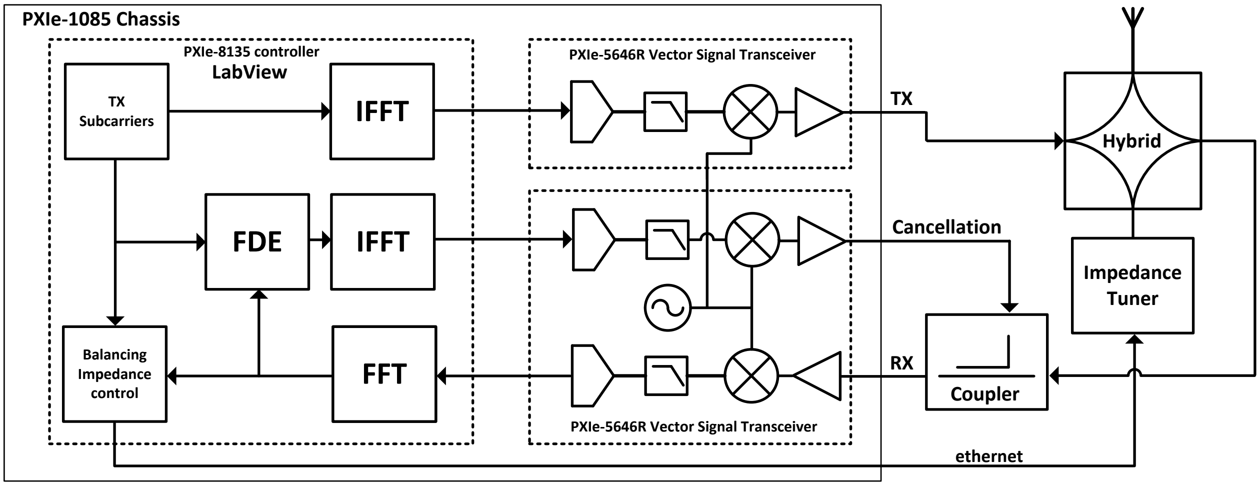

Fig. 3: Block diagram of the electrical balance and active cancellation (EBAC) full duplex transceiver prototype.

high isolation at that frequency. However, moving away from this frequency, the smith chart trajectories of the antenna system and the balancing network will diverge, limiting the isolation bandwidth. To obtain an extremely close match between the antenna and balancing impedance over a wide bandwidth would require a complicated balancing circuit topology with many tunable elements, and therefore in a practical system the isolation bandwidths is limited.

Measured impedance trajectories and the resulting TX-RX isolation of a prototype hardware EB duplexer are depicted in Fig. 2. The antenna used is a Taoglas PAD710 multiband cellular antenna, this being typical of a multiband cellular device, and a Focus Microwaves model 1808 electromechanical impedance tuner is used as the balancing impedance. These are connected through a Kryptar Model 1831 discrete hybrid coupler. The divergent behaviour of the impedance trajectories can clearly be seen in 2(a). The resulting measured TX-RX frequency response of the duplexer is depicted in 2(b), showing the limited isolation bandwidth caused by this impedance divergence. Full duplex transceivers require at least 50dB of RF domain isolation to prevent receiver saturation [4], and it is clear from Fig. 2(b) that this prototype EB duplexer cannot provide this over more that a few MHz of bandwidth. However it does provide >30dB of isolation over a 50MHz bandwidth, making it a viable alternative to using circulators or antenna separation.

B. Radio Frequency Cancellation

As with other full duplex architectures, the architecture presented in this paper performs radio frequency cancellation at the receiver input. The circulator based system in [4] uses passive analog cancellation, processing the RF transmit signal using analog circuitry. Since the cancellation signal is sampled after the TX chain, this has the benefit of replicating the self-interference components which arise from transmitter imperfections (e.g. phase noise and non-linearity [9]) in the cancellation signal. However, the cost and of analog signal processing is high, and in practical systems the ability of the system to replicate the self-interference channel may be limited. For example, in [4], the analog signal processing system comprises a 16-tap filter which is tuned to match the two dominant components of the self interference channel, these being due to the direct leakage through the circulator, and the signal reflected due to impedance mismatch at the antenna port, achieving a total isolation of 72dB over a 20MHz bandwidth [4]. This passive analog cancellation system works well for the simple self-interference channel dominated by the circulator leakage and antenna mismatch, but would be much less effective for more frequency selective self-interference channels. In dual antenna architectures, a frequency selective self-interference channel results from multipath propagation between the transmit and receive antennas [6], and the systems reported in [2], [6], [12] apply frequency selective transfer functions to the digital baseband transmit signal in order to replicate the frequency selective nature of the self interference channel, and then upconvert the baseband replica signal using an auxiliary transmitter to cancel self-interference in the RF domain. This technique has proven to be effective, with the systems reported in [2], [6] achieving >80dB isolation. By using this active technique, the accuracy of the replica signal is improved through high order filtering in DSP, however the disadvantage of this technique is the inability to cancel self-interference that results from transmit chain imperfections [9], and the cancellation performance is therefore limited by the EVM of both transmit chains. The cost, size, and power consumption of a second transmit chain is also a disadvantage, however in the EBAC architecture the auxiliary transmitter is required to operate at a much lower power (e.g. 40dB lower), requiring less amplification and thus mitigating this drawback. From Fig. 2, it is clear that the TX-RX channel of an EB duplexer is extremely frequency selective, exhibiting a magnitude variation of over 20dB across a 20MHz bandwidth, making active analog cancellation the most appropriate choice of RF cancellation technology for combination with EB duplexing.

III. Electrical Balance and Active Cancellation Prototype

A. Experimental setup

As a proof of concept, a prototype EBAC system was constructed and the performance measured. The discrete hardware EB duplexer described in section II was used as the

(a) f_c = 890MHz (b) f_c = 1890MHz

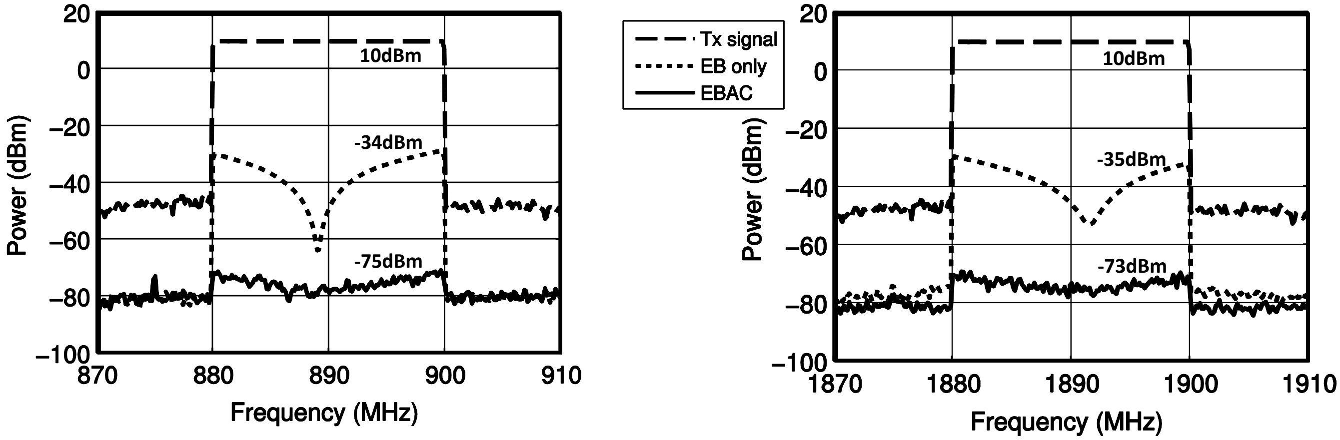

Fig. 4: Measured power spectra and integrated powers of the transmit signal, the self-interference after EB duplexing, and the self-interference after EB duplexing and active cancellation at 890MHz and 1980MHz.

EB sub-system, and combined with National Instruments PXIe system, comprising 2 PXIe-5646R Vector Signal Transceivers (VSTs) and a PXIe-8135 embedded controller, mounted in a PXIe-1085 chassis. The system is configured such that both transmitters and the receiver all share a common LO. The cancellation signal is injected just prior to the receiver input using a Mini-Circuits ZN2PD-9G-S+ combiner. All baseband DSP, including generation of the baseband cancellation signal and control of the balancing impedance, is written in LabView and runs on the embedded controller. In order to conveniently facilitate frequency selective cancellation, an LTE-like OFDM physical layer is implemented, allowing the self-interference channel to be estimated for each subcarrier. The full system architecture is depicted in Fig. 3, and the system operation is as follows. Firstly, the balancing impedance is tuned to maximise the EB duplexer isolation. This is performed using measurements of the self-interference channel through the EB duplexer and applying a gradient based optimisation algorithm to maximise the TX-RX isolation. Once the balancing impedance is set, the primary transmitter to receiver channel G_{TX-RX}, and the cancellation transmitter to receiver channel, G_{CX-RX} are measured. The EB and cancellation processes must occur in this order, as the balancing impedance setting is a key factor in determining G_{CX-RX} (as shown by (1)). The cancellation subcarrier IQ, $Cx(k)$, can then be calculated according to the following expression [2], [10]:

$$Cx(k) = -\frac{G_{TX-RX}(k)}{G_{CX-RX}(k)} \times Tx(k) \tag{2}$$

where $Tx(k)$ is the transmitted subcarrier IQ, and k is the subcarrier index. The cancellation subcarrier IQ generation is performed in the Frequency Domain Equalizer (FDE) sub-system, and the RF cancellation signal is generated from these subcarriers using the additional separate transmit chain. The system has a 20MHz bandwidth and a subcarrier spacing of 15kHz.

TABLE I: Comparison of EBAC TX-RX isolation performance against antenna separation and active analog cancellation (ASAC) systems, and circulator and passive analog cancellation systems.

Reference			Stage 1	Stage 1&2
This work, 890MHz		BW=20MHz	EB = 44dB	EBAC = 85dB
This work, 1890MHz		BW=20MHz	EB = 45dB	EBAC = 83dB
[2] ASAC	Config.A	BW=10MHz	AS = 34dB	ASAC = 58dB
[2] ASAC	Config.B	BW=10MHz	AS = 57dB	ASAC = 81dB
[6] ASAC		BW=20MHz	AS = 71dB	ASAC = 95dB
[4] Circ.+AC		BW=20MHz	Circ. ≈15dB	Circ.+AC = 72dB

B. Results

The TX-RX isolation provided by the prototype EBAC was measured at two carrier frequencies: 890MHz and 1890MHz. Fig 4 depicts the measured power spectra at the transmitter output, after the EB duplexing stage, and after EB duplexing and active cancellation. Mean isolation figures are summarised and compared with alternative methods in Table I. The TX-RX isolation provided by the EBAC architecture is >80dB in both the 890MHz and 1890MHz bands, clearly demonstrating that EB duplexing and active analog cancellation are complementary technologies well suited to combination in a full duplex architecture. There is very little difference between the TX-RX isolation in the two frequency bands, despite a separation of 1GHz, demonstrating the inherent tunability of this architecture. Comparisons are made against two antenna configurations reported in [2]: configuration B mounts the antennas at opposite ends of a laptop device, and configuration A places the antennas closer together on the same side of the device. Antenna decoupling in hand-held devices is a well researched topic [14], and configuration A would be much closer to the limited antenna isolation possible in a small form factor device. Configuration A is therefore a more relevant comparison against EBAC, which is a single antenna system suitable for small form factors. The prototype EBAC system presented here outperforms the systems reported in [2], [4], but falls short of the performance of the prototype in [6], which emulates a basestation deployment and utilizes separate antennas with relatively large physical separation, absorptive shielding, and cross-polar directional antennas. It is pertinent to note here that all of the other systems compared in Table I use off-the-shelf radios, which have a significantly higher EVM than the instrument grade VST radios used in this system (VST EVM is -43dB). However, even if the cancellation performance of this system were limited to around 25dB (as is achieved by the other systems), the TX-RX isolation would still exceed that achieved in [2] (config. A) and remain comparable to [4].

IV. Conclusion

Electrical Balance duplexing exploits electrical balance in hybrid junctions to couple the transmitter and receiver to a shared antenna, whilst providing high TX-RX isolation. Whereas multi-antenna architectures and circulator based designs may increase the size and cost of the system, EB duplexing can be implemented on chip, and is widely tunable, making it attractive for use in low cost small form factor full duplex devices.

The typically divergent nature of the antenna and balancing impedances limits the isolation bandwidth of the EB duplexer, and EB duplexing alone may not provide the necessary level of RF isolation. However, when combined with active analog cancellation, the RF isolation requirement can be fulfilled, and EB is therefore a viable alternative to using separate transmit and receive antennas, or connecting a shared antenna using a circulator.

A novel full duplex transceiver architecture combining electrical balance duplexing and analog cancellation is implemented. The measured TX-RX isolation is compared against alternative full duplex architectures reported in the literature. The prototype EBAC transceiver achieves >80dB TX-RX isolation. The achievable isolation is less that that observed in antenna separation architectures with relatively large antenna separations, however the isolation compares favourably against antenna separation systems with limited antenna isolation, as would be the case in small form factor devices. The performance of the EBAC prototype is comparable to the performance of circulator based systems which have been reported. Similar TX-RX isolation was achieved at both 890MHz, and 1890MHz, demonstrating the inherently wide tunability of this architecture.

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